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NORFOLK, VIRGINIA

THE DYNAMIC RESPONSE OF NAVAL STRUCTURES TO THE APPLICATION OF A LOADING FUNCTION TO PREDICT UNDERWATER EXPLOSIONS

By

Dennis J. Fallon, Principal Investigator

Final Report
For the period July 10 to December 31, 1984

Prepared for the
Head Mechanics Division
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217

Under
Contract N00014-84-K-0607
Philip A. Harless, Contracting Officer

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The structural response of surface ships to a shock environment is a very important problem in naval research. Specific research emphasis is on hull structure integrity (or watertightness) and the integrity of equipment aboard a surface ship due to explosions.

The fundmental characteristic of the shock experienced aboard naval vessels is the sudden increase in the velocity of structural members.

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Equipment supported by these structural members may be adversely affected by this sudden increase in motion. There are two basic types of damage ~~[1]~~ to equipment which concern the naval designer: mechanical damage and maloperation. Mechanical damage manifest in the rupture or permanent deformation of the equipment's structural members. The equipment is considered to have failed if the structural damage is so severe the equipment can no longer perform its intended function. Maloperation occurs when the shock causes significant changes in the function being performed by equipment, albeit no structural failure has occured. An example of maloperation is the stopping of an electrical motor when the shock disrupts the function of the motor controller.

The shock loading of a surface ship may result from three sources [1]: 1) underwater non-contact explosions, 2) contact explosions, and 3) air blast from aerial bombs or from the vessel's own armament. Research is being performed at the Underwater Explosions Research Division (UERD) located in Portsmouth, ~~Virginia~~, a division of the David Taylor Naval Ship Research and Development Center, to model the shock loading of underwater non-contact explosions on surface ships. This research has culminated in the development of a new loading function to approximate the shock loading. This function emphasizes the structural response while de-emphazing the complex fluid-structure interaction, thereby considerably simplifying the analytical calculations of the dynamic response.

The purpose of this report is to illustrate the application and simultaneously demonstrate the accuracy of this new loading function. Two test vehicles were chosen to compare analytical results to actual experimental results. The first is the structural analysis of the "Paddlewheel" and the second is the structural analysis of the USS SPRUANCE (DD-963). The exact details and the results of these two tests are confidential and as such will not be presented in this report.

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THE DYNAMIC RESPONSE OF NAVAL STRUCTURES TO THE APPLICATION OF A LOADING FUNCTION TO PREDICT UNDERWATER EXPLOSIONS

By

Dennis J. Fallon*

INTRODUCTION

The structural response of surface ships to a shock environment is a very important problem in naval research. Specific research emphasis is on hull structure integrity (or watertightness) and the integrity of equipment aboard a surface ship due to explosions.

The fundamental characteristic of the shock experienced aboard naval vessels is sudden increase in the velocity of structural members. Equipment supported by these structural members may be adversely affected by this sudden increase in motion. There are two basic types of damage [1] to equipment which concern the naval designer: mechanical damage and maloperation. Mechanical damage manifests in the rupture or permanent deformation of the equipment's structural members. The equipment is considered to have failed if the structural damage is so severe that the equipment can no longer perform its intended function. Maloperation occurs when the shock causes significant changes in the equipment's function, albeit no structural failure has occurred. An example of maloperation is the stopping of an electrical motor when the shock disrupts the function of the motor controller.

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The purpose of this report is to illustrate the application and simultaneously demonstrate the accuracy of this new loading function. Two test vehicles were chosen to compare analytical results to actual experimental results. The first is the structural analysis of the "Paddlewheel" and the second is the structural analysis of the USS SPRUANCE (DD-963). The exact details and the results of these two tests are confidential and as such will not be presented in this report.

ANALYSIS OF SUBMARINE HULL PENETRATION TEST VEHICLE

General Remarks

The need to find an economical and reliable method to shock qualify small hull penetration on submarines is a very important problem in naval research. The methods currently employed are the Full Scale Section (FSS) and the Submarine Shock Test Vehicle (SSTV). These test vehicles model a portion of a submarine's hull by use of a large stiffened cylindrical section. Hull penetrations mounted in these test vehicles are subjected to a shock environment similar to an actual submarine during an underwater explosion. Due to the size of these two test vehicles and the intricate handling required, the cost of conducting shock qualification tests for a single

small hull penetration is prohibitive.

An attractive alternative to the full scale test vehicle for testing small hull penetrations is the "Paddlewheel" (named for its appearance). Penetrations are tested by mounting them to a flat circular plate attached to a rigid baffle type structure (Figure 1). Since this test vehicle is significantly smaller than the full scale test vehicle, and the installation of the test items require less time, there is a considerable savings in cost.

On March 6, 1984, a "Paddlewheel" test was conducted in the Turning Basin located in the Norfolk Naval Shipyard in Portsmouth, Virginia. As previously mentioned, the actual details and results of this test are confidential. Interested readers are referred to reference 2 for specific test information. The purpose of this section is to discuss the new load model as it applies to the analysis of the Paddlewheel, the finite element structural model used in the analysis, and to compare the analytical and experimental results.

Loading Function

To simulate the pressure from an underwater explosion on a thin air-backed plate, a rectangular impulse function is derived by equating the impulse of the load to the momentum of the plate acting with a velocity calculated by Taylor Plate Flat Theory (3). The Taylor Plate velocity is calculated by the following expression:

$$V = \frac{2\,P_o}{\rho\, c}\, Z^{\frac{Z}{1-Z}} \qquad (1)$$

where $Z = m/\rho c\theta$

θ = decay constant from the similitude equation;

P_o = peak pressure from the similitude equation;

c = speed of sound in water;

ρ = mass density of water;

m = mass density of the target plate.

An approximate time duration of the rectangular impulse function is evaluated from the following expression:

$$t = m/\rho c \tag{2}$$

However, parametric studies performed as a part of this work indicate that the analytical results are insensitive to the time duration.

As previously mentioned, by equating the impulse of the loading to the momentum of the plate with a velocity given by equation (1) the following equation is derived to evaluate the peak pressure:

$$F = \frac{mV}{t} \tag{3}$$

In the experiment, a 1-7/8" thick plate was used for the target. Using equations (1) through (3) with the weight and standoff distance of the charge specified in reference 2, the time duration of the loading was calculated to be 1/4 milliseconds with a maximum pressure of approximately 6,300 pounds per square inch.

Structural Modeling

A finite element model was generated to evaluate the dynamic response of the plate. All analysis was performed by use of the standard finite element code SAP (Structural Analysis Program). SAP [4] is a linear, elastic, static or dynamic finite element software developed by structural researchers at the University of California.

The structural model, illustrated in Figure 2, consisted of modeling one quarter of the plate (using symmetry) by 42 four-noded quadrilateral finite elements. Each element is formed from four compatible triangular elements with six degrees of freedom per node. One quarter of the simulated hull penetration's mass was lumped at the center of the plate. The translation displacements of the nodes on the outer edge of the plate was assumed to be fixed. This assumption was justified due to the large mass of the cylinder and the water behind the test vehicle relative to the mass of the plate.

The fundamental characteristic of an underwater explosion is a very short time duration with an extremely high peak pressure. Under this type of loading the higher frequencies in the dynamic analysis contributes significantly to the overall response of the system. To ensure that higher frequencies were included in the analysis, the computation of the plate's response was performed using step by step integration through the time domain on the coupled differential equation of motion. An integration time step of 8×10^{-4} milliseconds was selected after performing convergent studies. The total time of integration was 2.4 milliseconds.

Analysis Results

The analytical and experimental results are compared in Figure 3.

(All values have been normalized for security reasons.) As illustrated in this figure excellent agreement was obtained. Specifically, the finite element technique approximated the experimental results to within four percentage points. Figure 4 illustrates the effect varying the boundary condition from a clamped end to a simply supported end has on the evaluation of the velocity. As depicted the response period of the clamped end is shorter than the simply supported (as expected since the clamped ends is a stiffer system than the simply supported ends); but, the peak velocity was insignificantly effected.

An additional investigation was conducted to evaluate the effects the penetration's mass has on the prediction of the peak velocity. As illustrated in Figure 5, this mass significantly effects the estimation of the peak velocity. Specifically, the velocity without the mass at the center was fourteen percent higher than when the mass was included. A small mass at the center of a circular plate has an insignificant effect on the lower frequencies, but greatly effects the evaluation of the response of the higher frequencies of vibration (5). As previously mentioned, the higher frequencies contribute significantly to the dynamic response of structures subject to an underwater explosion.

As an additional verification of the results, a finite element analysis was performed on a one-inch plate of a Paddlewheel tested in 1973 [6]. Figure 6 compares the analytical and experimental results which agree to within nine percent.

ANALYSIS OF USS SPRUANCE (DD-963)

General Remarks

The USS SPRUANCE (DD-963), commissioned on September 20, 1975, was the

first of a new class of destroyers developed for submarine warfare. The SPRUANCE is 563 feet long with a beam of 55 feet and an overall displacement of 7800 tons. The complement consisted of 296 officers and enlisted men [7].

The USS SPRUANCE was shock tested on 7 and 8 of March 1976. The details and the actual results of this test are confidential; interested readers should refer to reference [8] for specific test information. The objective of this section is to discuss the new load model as it applies to the analysis of a surface ship, the finite element representation of the SPRUANCE, and to compare the analytical and experimental results.

Loading Function

A loading function for the analysis of surface ships is derived in a similar manner as the loading function previously used for the analysis of the "Paddlewheel". Specifically, a rectangular impulse function is derived by equating the impulse of the load to the momentum of a nodal point (see Structural Model). However, the initial velocity of the node is obtained by use of the "spar buoy" model [9]. The fundamental assumption of the "spar buoy" model is the structural node is kicked off with the same average velocity as an equivalent column of water in the free field. The equation to compute this velocity is given by:

$$V = \int_0^d u(y)dy \qquad (4)$$

where d is the average draft of the ship; u(y) is the kick off velocity of a particle of water in the free field given by:

$$u\,(y) = \frac{2\,P_o\,\mathrm{Cos}\,\beta}{\rho c}\,\exp\,\frac{-2y\,\cos\,\beta}{c\theta} \tag{5}$$

where β is the angle of incident of the shock; and all other terms have been previously defined.

An approximate time duration of the impulse function is evaluated from the following expression:

$$t = \frac{m'\,\mathrm{Cos}\,\beta}{\rho c} \tag{6}$$

where m' is the average mass per square incn treating the ship as an equivalent plate. However, as previously mentioned, parametric studies indicate the analytical results are insensitive to the time duration. The results depend on the total momentum imparted to the node due to the loading function. Using the previous equation, a peak loading pressure is obtained by use of equation (3).

Structural Model

A finite element mathematical model consisting of forty flexure beam elements was used to evaluate the dynamic response of the SPRUANCE. The elements' section properties (moment of inertia and cross sectional area) as well as the weight distribution were obtained from a private communication from the Naval Sea Ship Command (NAVSEA). Previous work [10] has demonstrated that the higher frequencies of vibration are significantly effected by the exclusion of shear deformation. However, the evaluation of the contribution of the shear energy via the calculation of the effective shear area is a very complex problem for ship structures. To obtain an approxi-

mate value the data in reference 11 was used to calculate an effective shear area of about 30% of the actual cross sectional area. Varying this percentage ± 10% had insignificant effect on the response. The total mass of each element was lumped at each node.

As with the "Paddlewheel" the dynamic response of the SPRUANCE was calculated by using step-by-step integration through the time domain. The kinematic boundary conditions for the ship was assumed completely unrestrained. Proper consideration was given to the arrival of the shock wave at each individual node. Gravity and atmospheric pressure was accounted for by use of a concentrated load applied at the cut-off of the impulse load.

ANALYSIS OF RESULTS

The analytical results were compared to the experimental data at three points on the ship: stern, amidship and the bow. Figures 7 to 9 compare the experimental and analytical velocities at these three points. As generally illustrated in these figures very good agreement was obtained. The maximum velocity at the stern and amidship compared quite favorably; whereas, the peak velocity at the bow did not agree as favorably. This difference, as well as the more erratic behavior of the experimental curve, is due in part to local vibration of the structural members supporting the velocity meters during the test.

Figures 10 through 12 compares the experimental and analytical displacements. The experimental displacements were obtained by numerically integrating the experimental velocities. As illustrated, the results are in fair agreement with the maximum difference being at the bow section. (This is to be expected considering the difference in velocities of the experi-

mental and analytical results.) The general shape of the displacement curves are quite similar.

CONCLUDING REMARKS

Exciting research work is presently being performed at the Underwater Explosions Research Division to predict the dynamic effect of underwater explosions on surface ships. Using the load function developed by researcherat UERD, a very good estimate of the dynamic response of the Paddlewheel and surface ships can be predicted, as the results of this study indicate. However, the analysis performed in this study represents only the first step. Continuing work at UERD is underway to refine the mathematical models. Additional studies need to be performed to see how this work can be extended to submarines, a very important area of study in naval research.

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The author of this report wishes to acknowledge the contribution of his research colleagues at the Underwater Explosions Research Division. Noteworthy is the contribution Mr. John Gordon is making to naval research in the development of the loading function used in this report. The writer wishes to thank Mr. Fred Costanzo for his invaluable assistance in using the computer facilities at UERD. Mr. Ron Dawson is thanked for his assistances in understanding the results from the Paddlewheel test. Mr. Vernon Bloodgood, former group leader, and Mr. Mike Riley, present group leader, are thanked for their encouraging support during this work. Finally, but not lastly, Mr. Robert Fuss, Division Head, is thanked for his support of this work.

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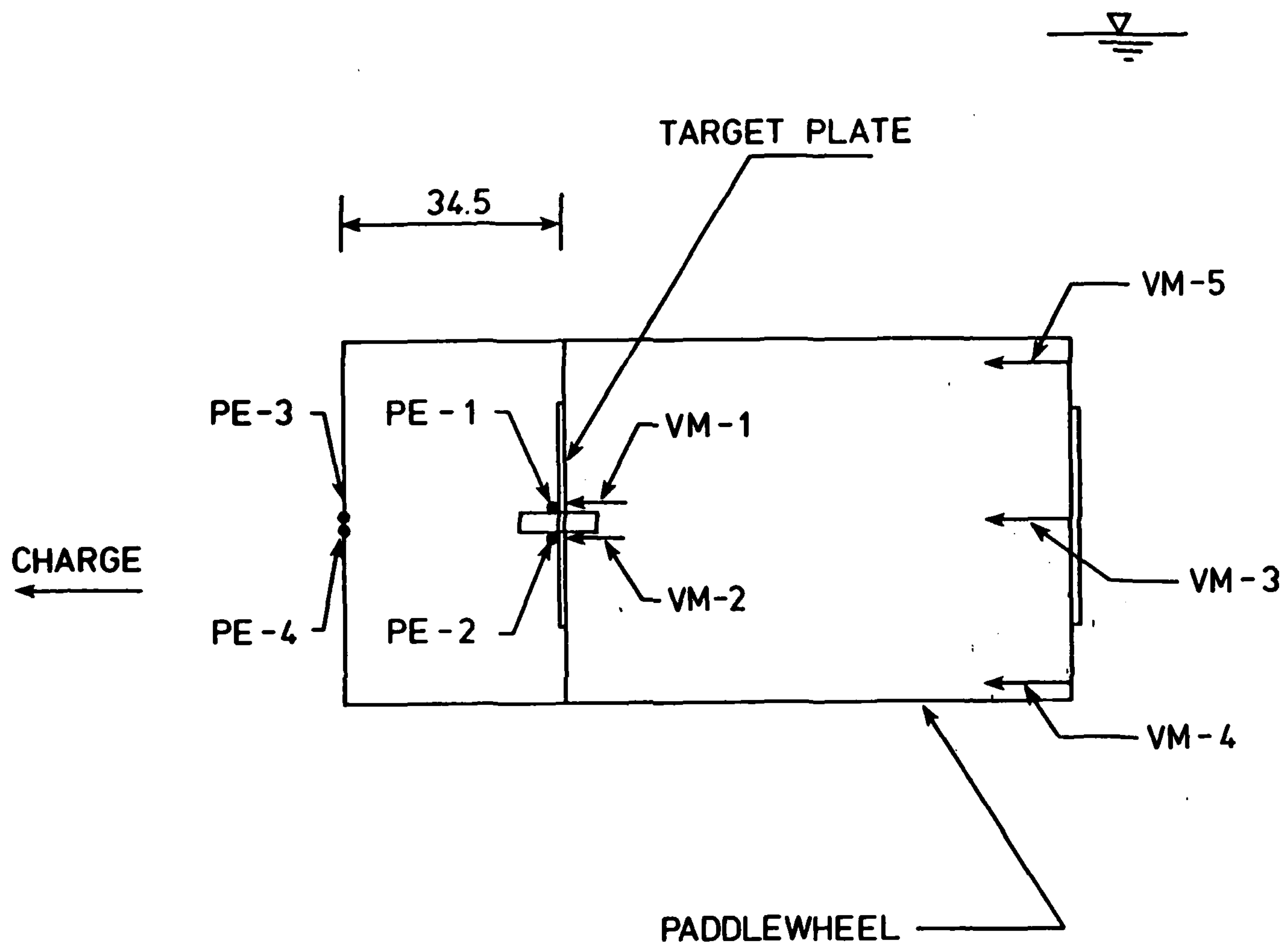

Figure 1. Details of Paddlewheel.

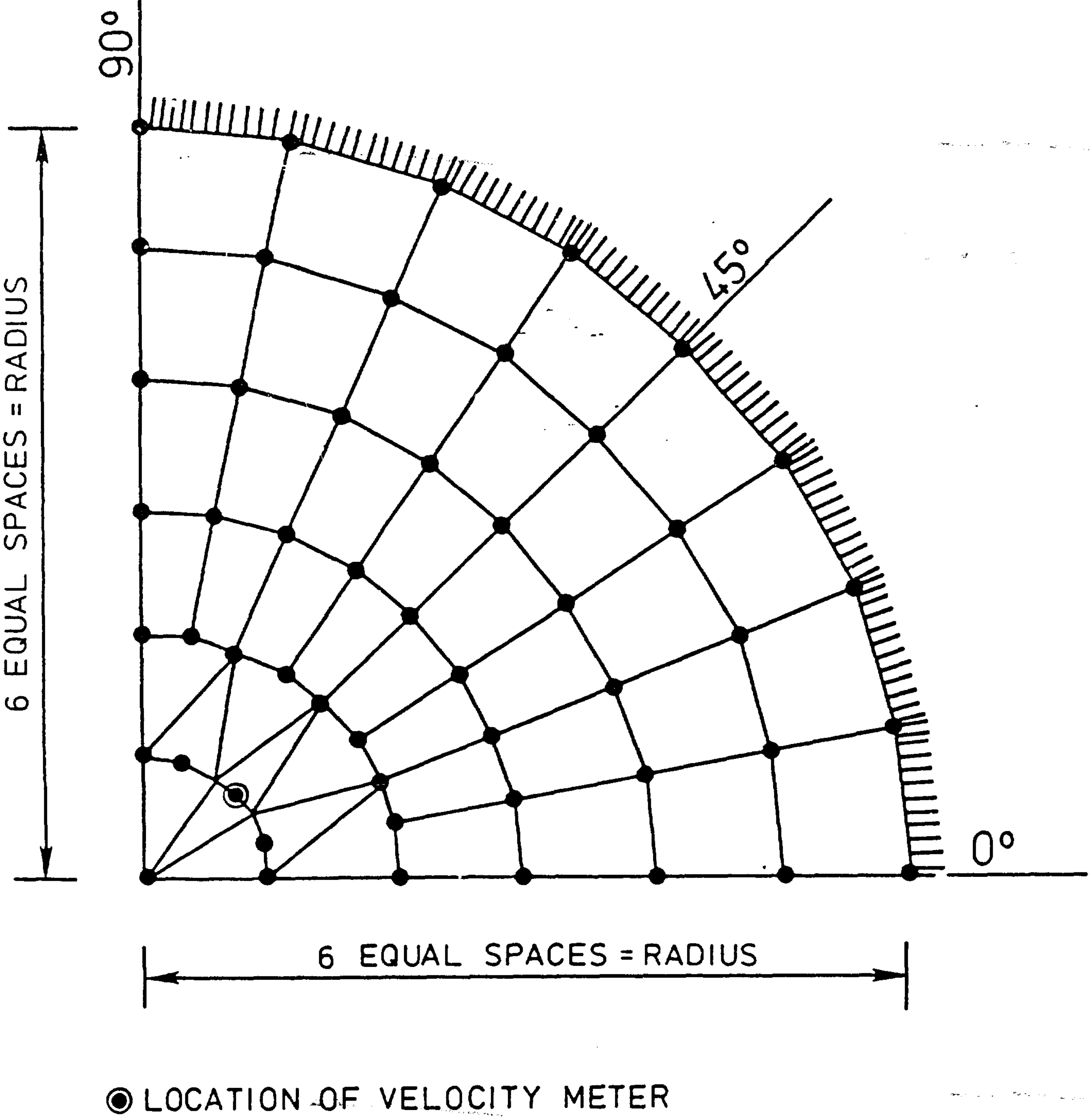

Figure 2. Finite Element Model of the Paddlewheel.

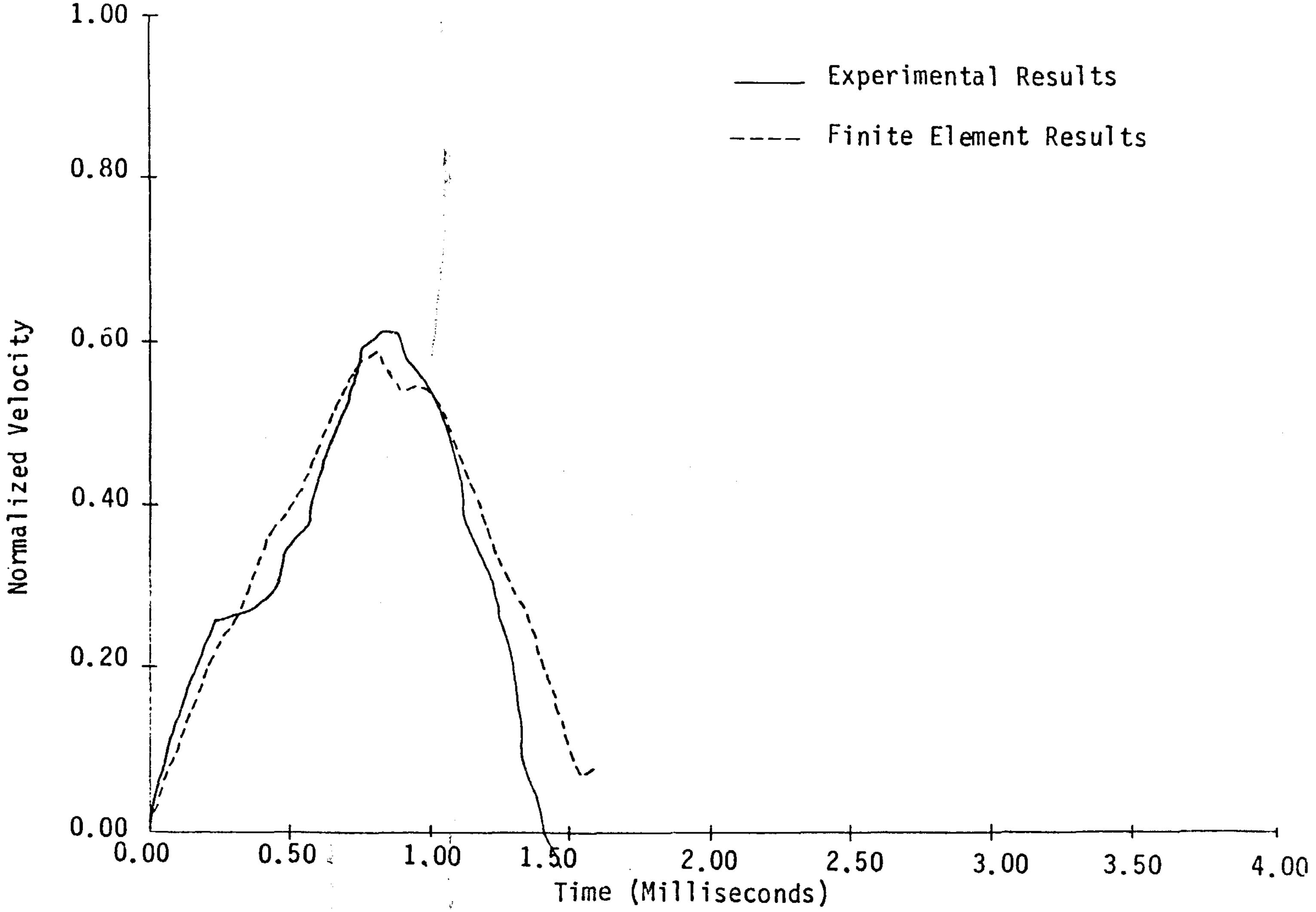

Figure 3. Comparison of Experimental and Finite Element Results for Paddlewheel.

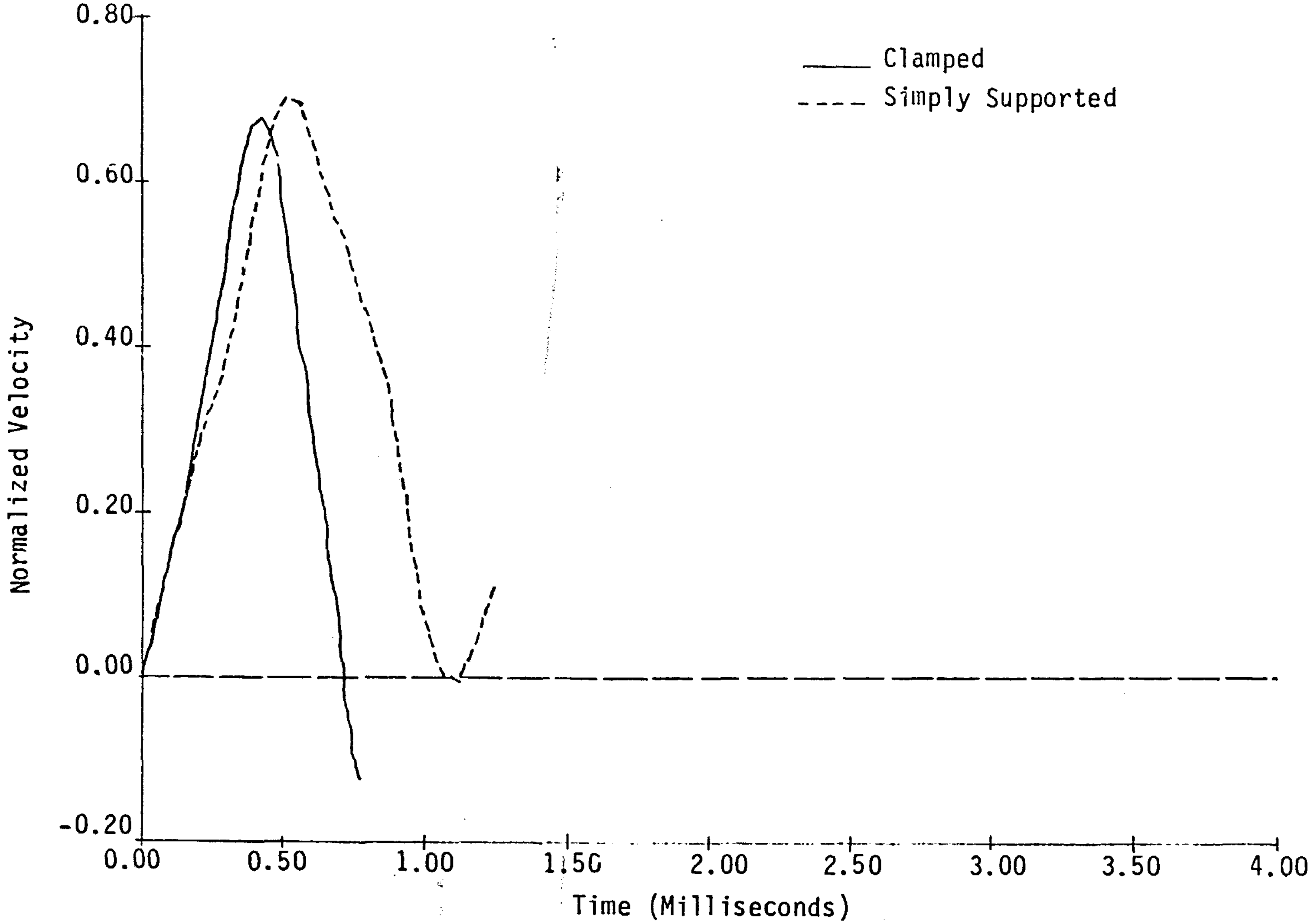

Figure 4. Effects of Boundary Condition on Paddlewheel Analysis.

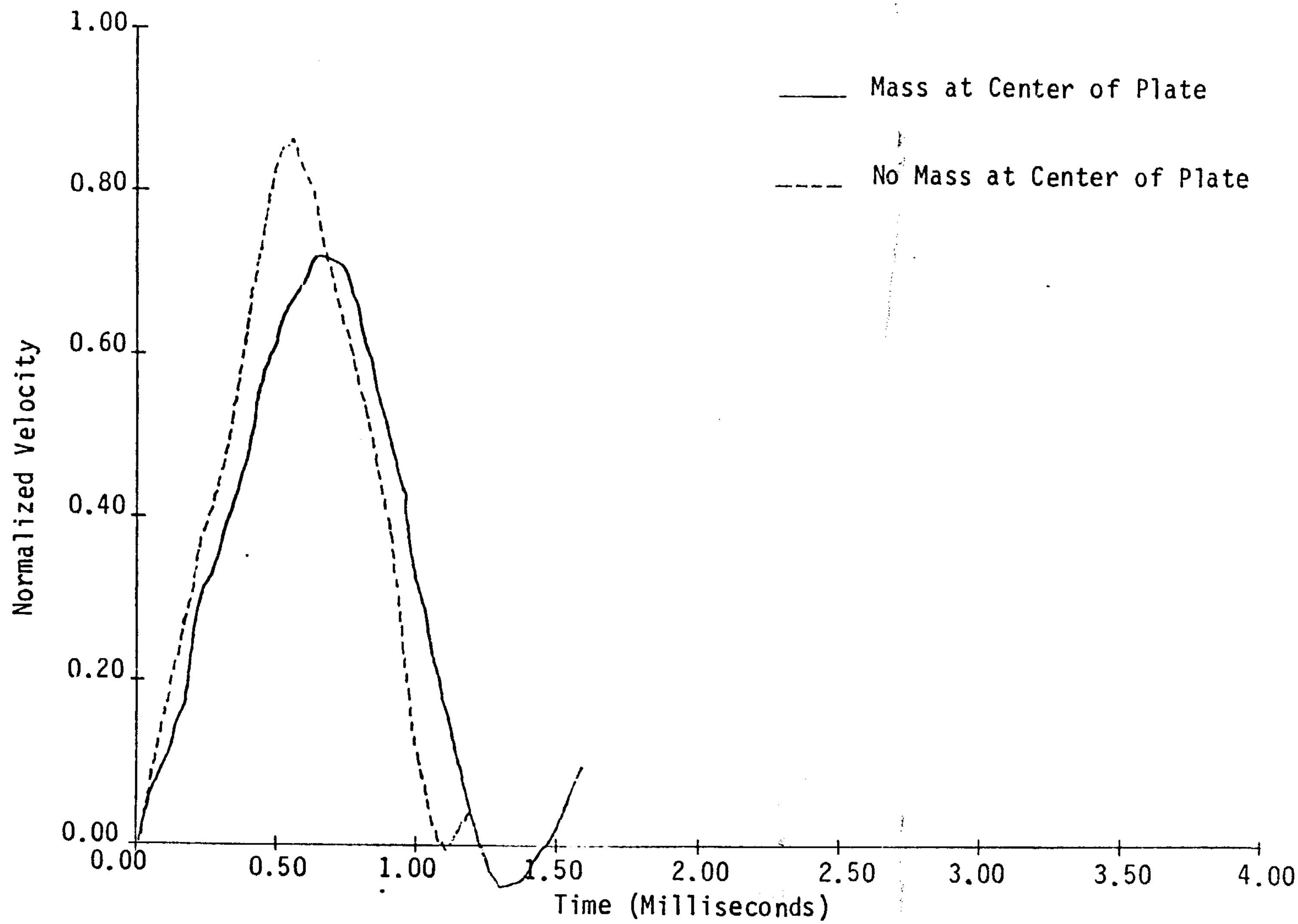

Figure 5. Effect Penetration Mass has on Velocity of Paddlewheel.

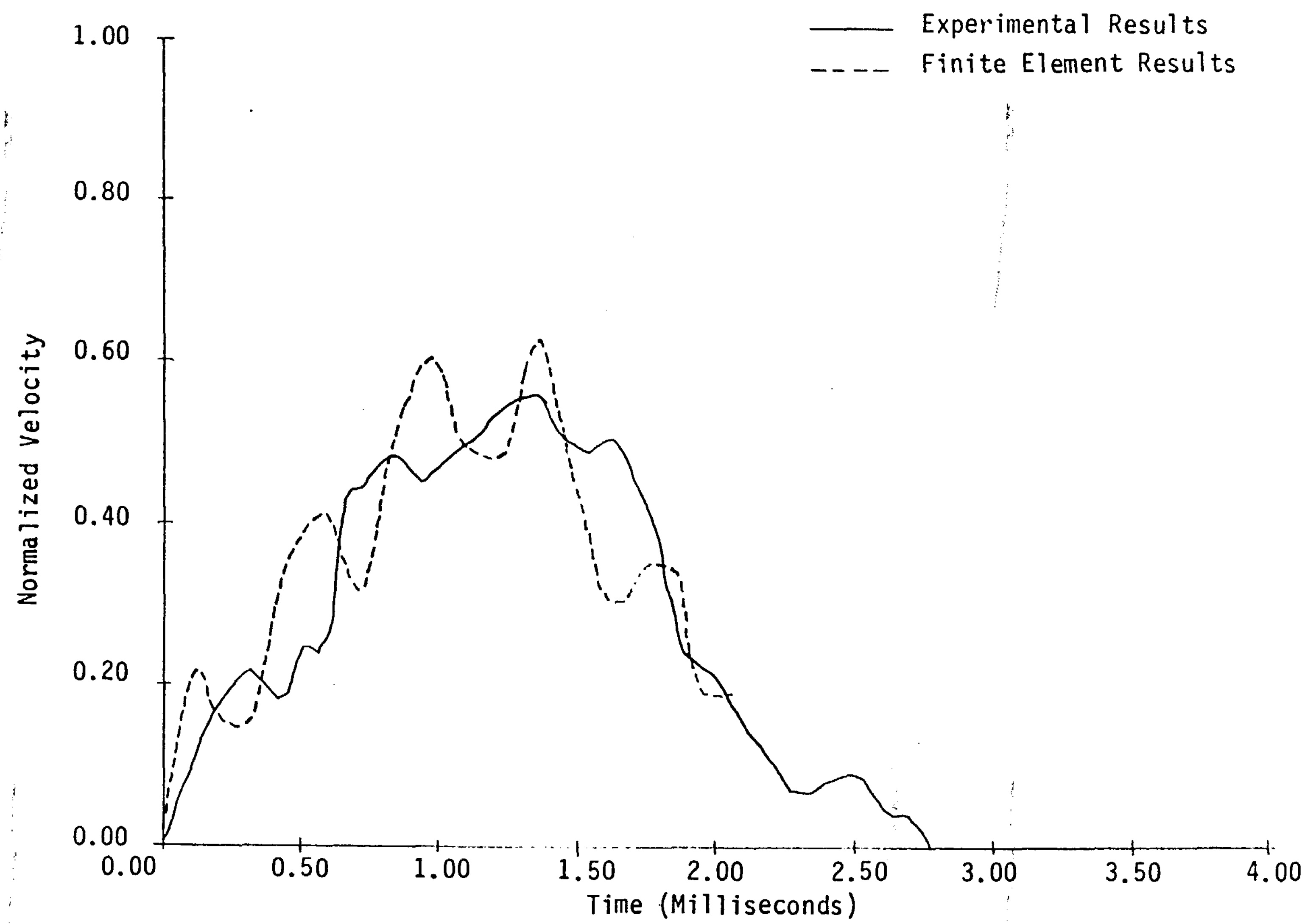

Figure 6. Analysis of One Inch Plate.

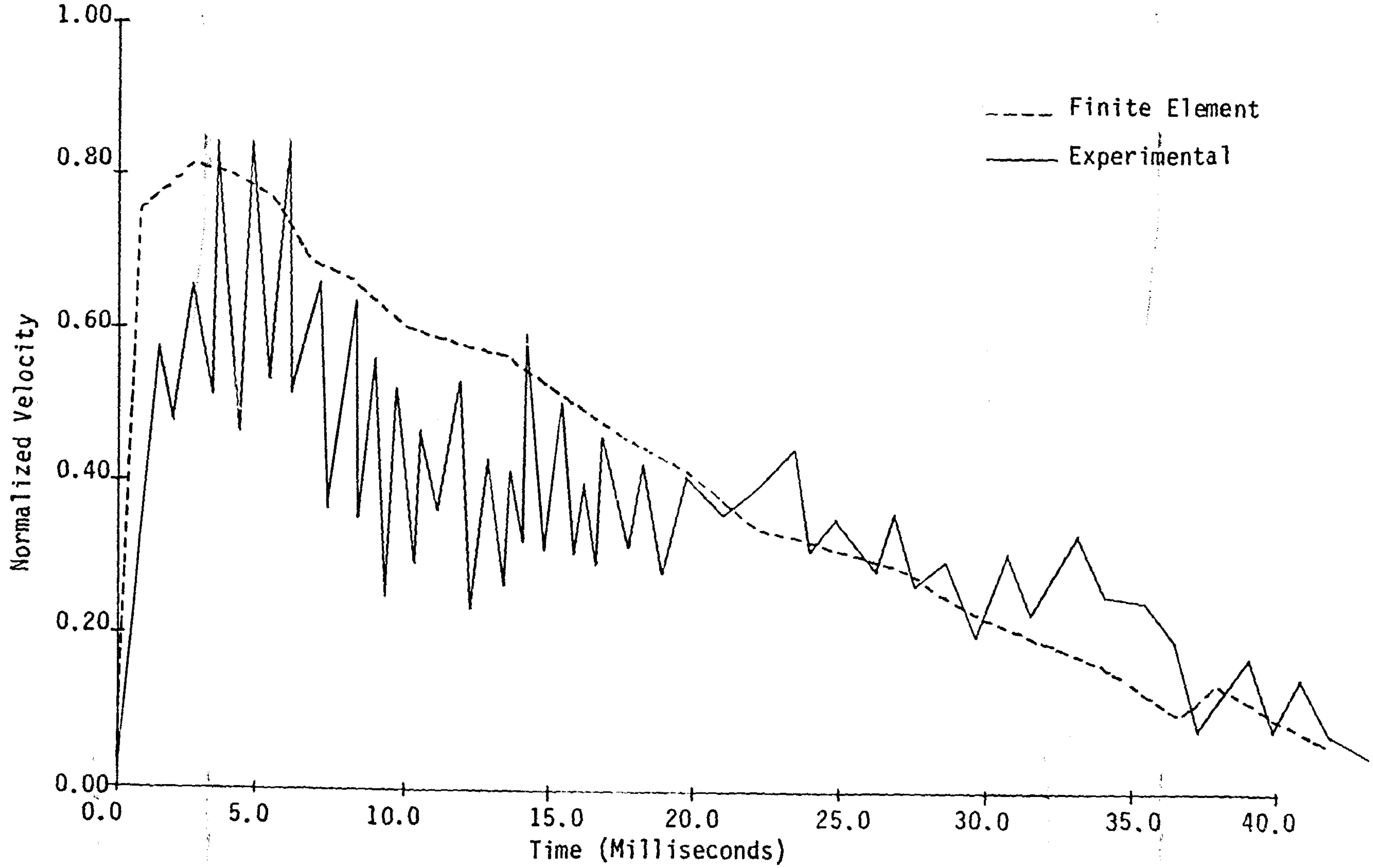

Figure 7. Velocity at Amidship.

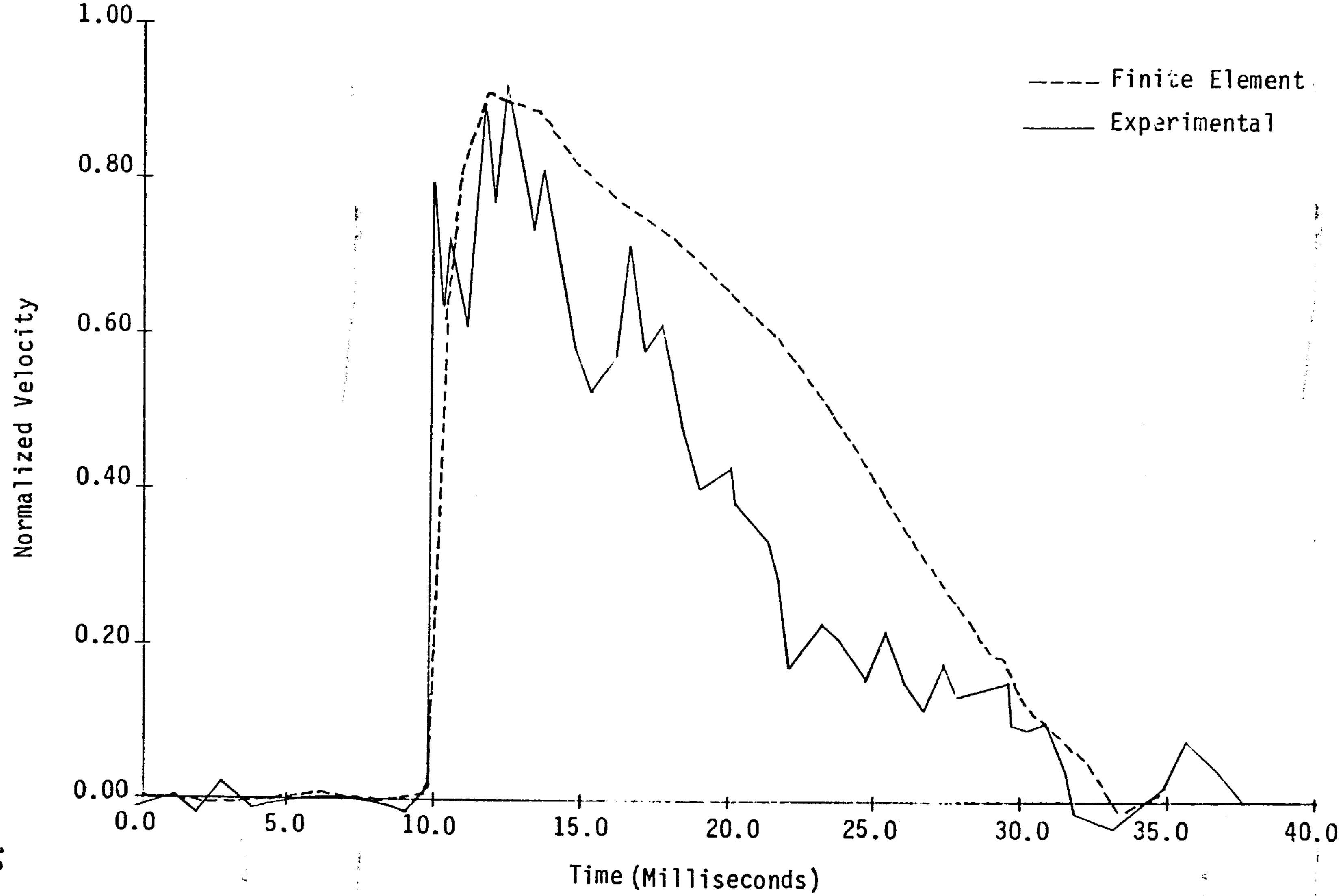

Figure 8. Velocity at Stern.

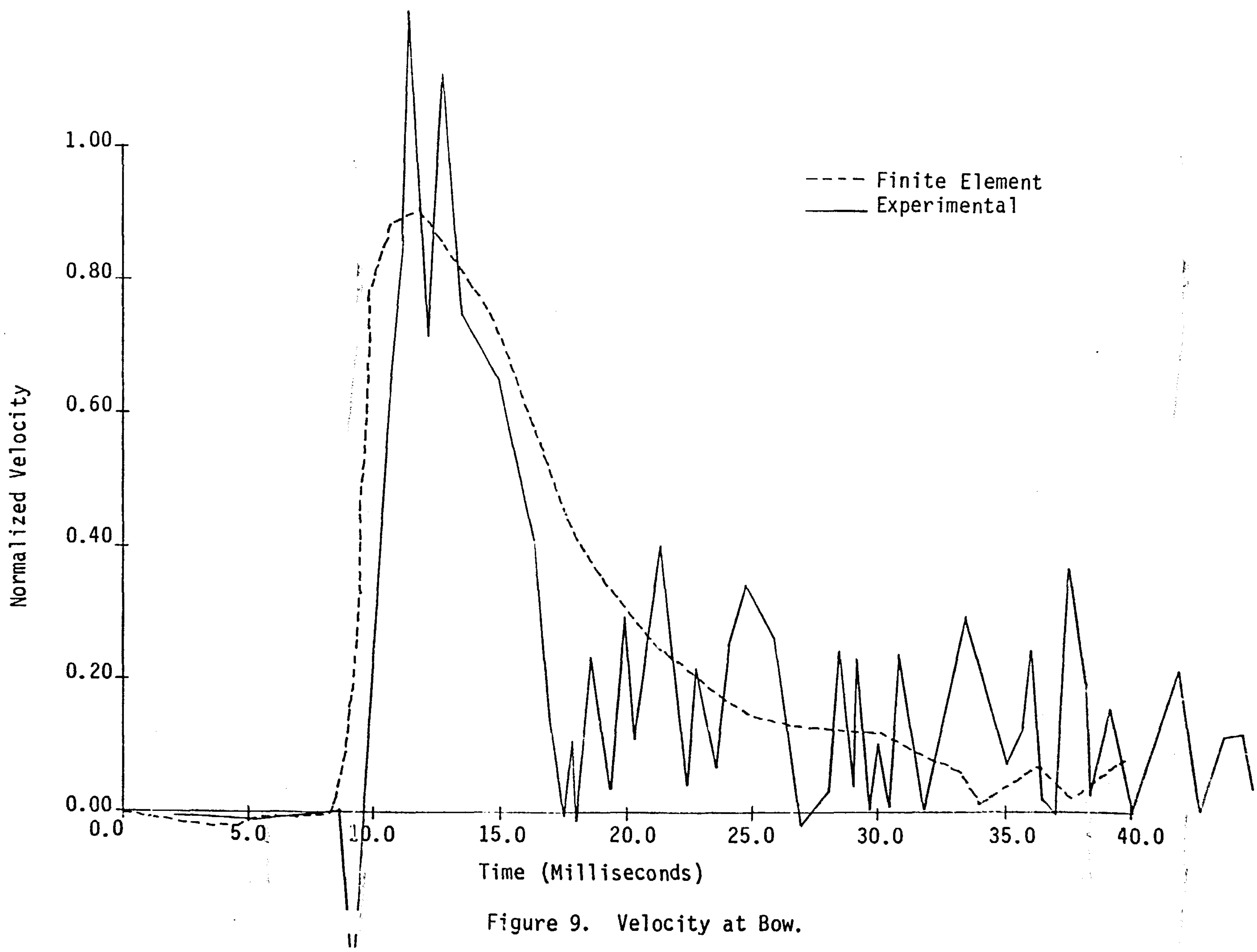

Figure 9. Velocity at Bow.

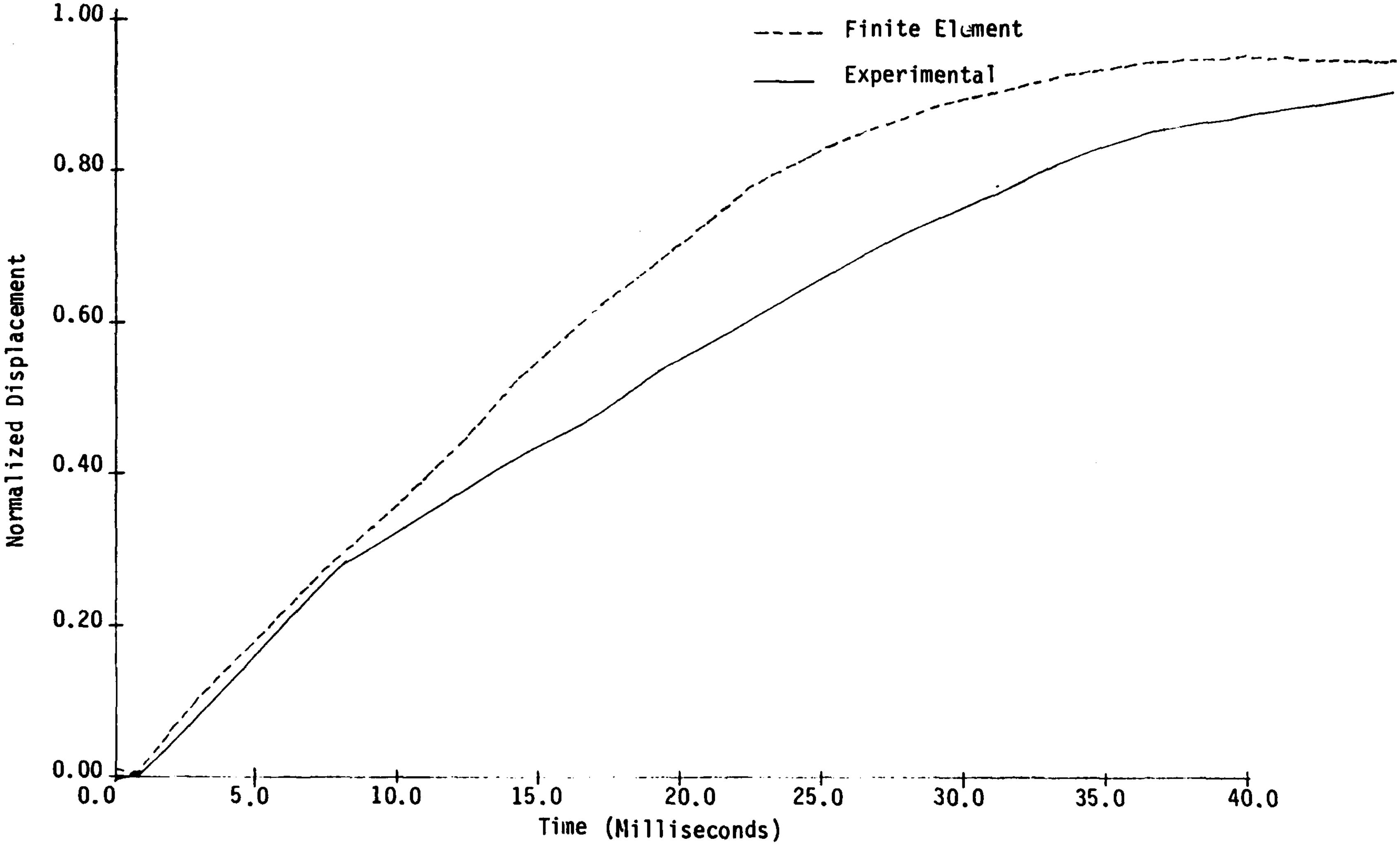

Figure 10. Displacement at Amidship.

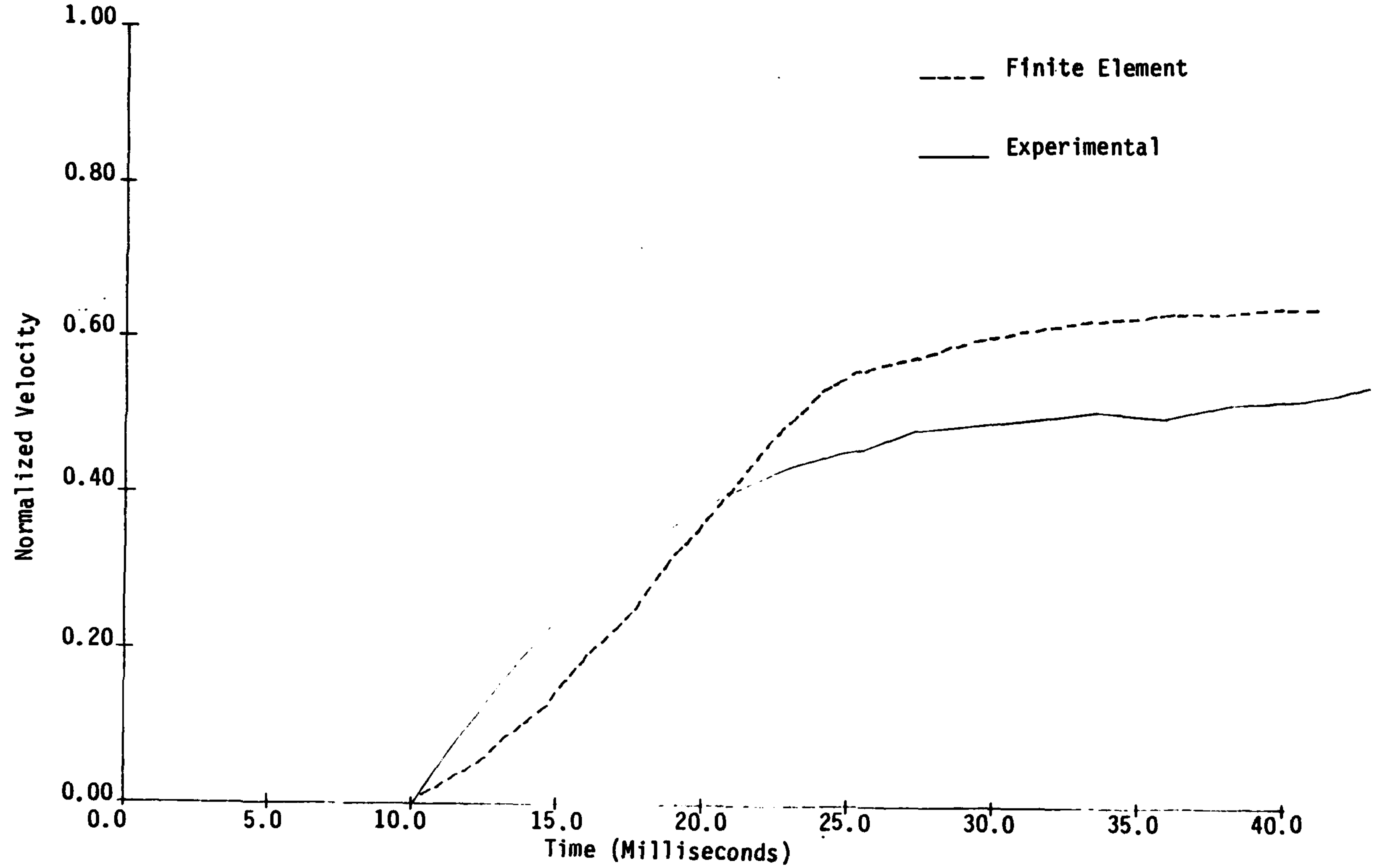

Figure 11. Displacement at Stern.

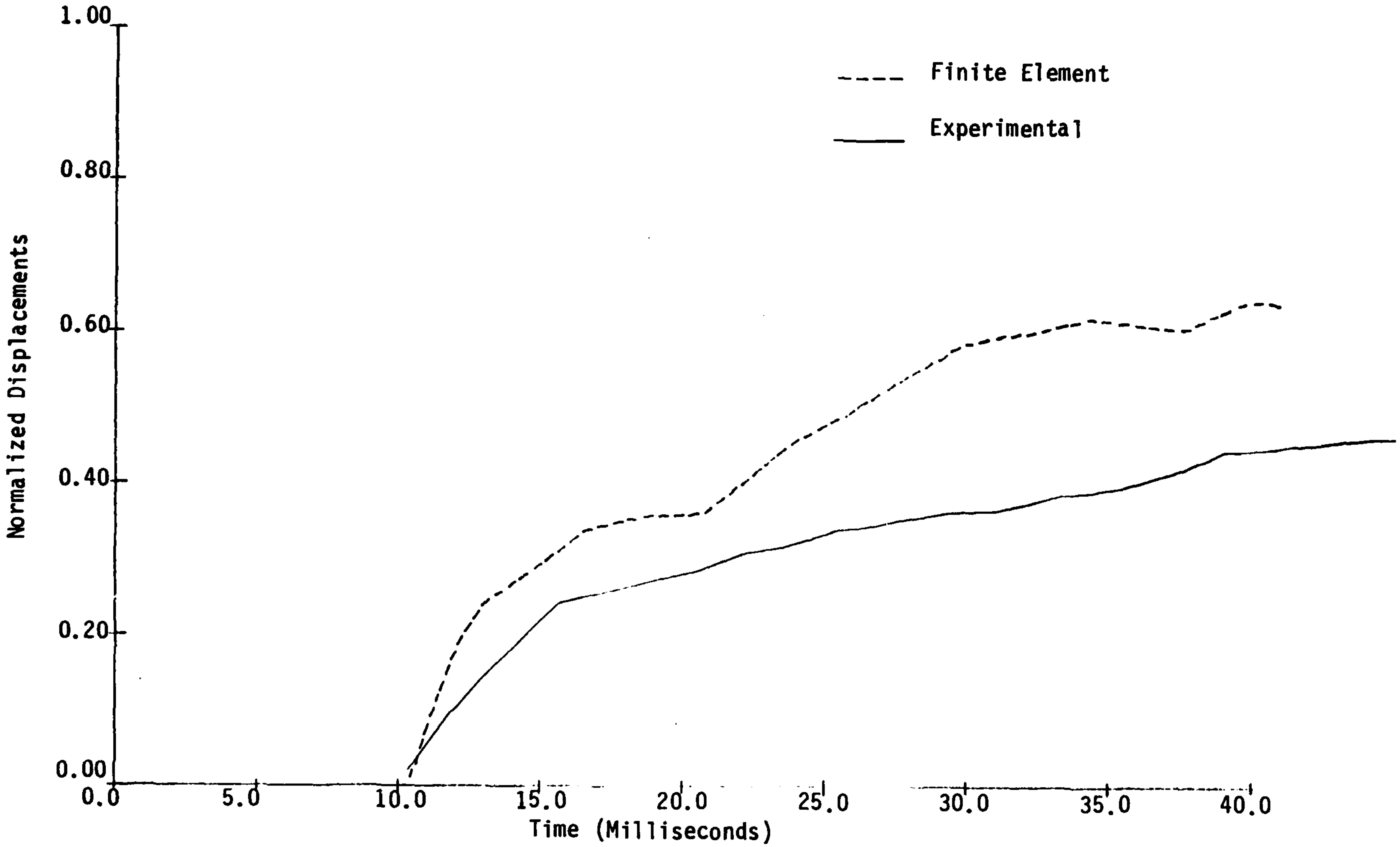

Figure 12. Displacement at Bow.